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# Mid-Cretaceous thrusting in the southern Coast Belt, British Columbia and Washington, after strike-slip fault reconstruction

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**Abstract.** A major thrust system of mid-Cretaceous age is present along much of the Coast Belt of northwestern North America. Thrusting was concurrent, and spatially coincided, with emplacement of a great volume of arc intrusives and minor local strike-slip faulting. In the southern Coast Belt (52° to 47°N), thrusting was followed by major dextral-slip faulting, which resulted in significant translational shuffling of the thrust system. In this paper, we restore the displacements on major dextral-slip faults of the southern Coast Belt and then analyze the mid-Cretaceous thrust system. Two reconstructions were made that use dextral faulting on the Yalakom fault (115 km), Castle Pass and Ross Lake faults (10 km), and Fraser fault (100 km). The reconstructions differ in the amount of dextral offset on the Straight Creek fault (160 and 100 km) and how much the NE part of the Cascades crystalline core expanded (30 km and 0 km) during Eocene extension. Reconstruction A produces the best match of lithotectonic units and thrust systems. Our synthesis shows that the southern Coast Belt thrust system was ≥250 - 180 km wide after thrusting. The thrust system was mainly southwest vergent but had a belt of northeast vergent back thrusts on the northeast side associated with the Tyaughton-Methow basin, which may indicate large-scale tectonic wedging. Thrust faults are commonly low to moderate angle, but high angle faults also occur, especially as late stage, out-of-sequence, structures involving plutons. The amount of thrust displacement across the system is unknown but must be at least 100 km and may be many hundreds of kilometers. Most thrusting occurred from ~100 to ~80 Ma and did not migrate systematically until after ~90 Ma, when thrusting and magmatism shifted to the northeast for a few million years. Widespread thrusting occurred both near plutons and where there are no (or small) plutons, which strongly suggests that thrust faulting was caused by regional- to plate-scale forces such as rapid plate convergence and/or arc-continent collision.



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## Introduction

The Coast Belt in the northwestern Cordillera of North America contains the roots of the largest Mesozoic magmatic arc in North America, which is cut by a mid-Cretaceous, synmagmatic thrust system over much of its length (Figure 1) [*Rubin et al.*, 1990]. This thrust system is especially well defined in SE Alaska [*Brew et al.*, 1989; *Rubin et al.*, 1990; *Gehrels et al.*, 1992; *Haeussler*, 1992; *McClelland et al.*, 1992; *Rubin and Saleeby*, 1992] and the southern Coast Belt of SW British Columbia and NW Washington (Figure 1) [*Crickmay*, 1930; *Misch*, 1966; *Davis et al.*, 1978; *Brown*, 1987; *Rusmore and Woodsworth*, 1991a, 1994; *Miller and Paterson*, 1992; *Journeay and Friedman*, 1993; *Schiarizza et al.*, 1990]. The mid-Cretaceous thrust system in the southern Coast Belt is the focus of this paper. This deformation episode (~100 - 80 Ma) is the major tectonic event in the belt, during which there was voluminous magmatism and metamorphism and basins subsided and were inverted. Deformation continued after ~80 Ma, but it changed significantly to a narrower belt dominated by strike-slip and thrust faulting and less voluminous magmatism. Thus the southern Coast Belt is a prime example of a complex, synmagmatic thrust belt that was overprinted by major strike-slip faults.

The cause of the mid-Cretaceous contraction in the Coast Belt is controversial. In one hypothesis, the final accretion of the Insular superterrane involved an oceanic arc-continental arc collision that caused regional contraction as the outer plate (Insular terrane) continued to subduct and collide with North America [*Monger et al.*, 1982; *Thorkelson and Smith*, 1989]. In a second model, the regional contraction results from the telescoping of a small back arc or transtensional basin between the Insular superterrane arc to the west and the western edge of North America [*McClelland et al.*, 1992; *van der Heyden*, 1992]. A third model relates thrusting to contractional step over zones in a major dextral strike-slip fault system [*Brown*, 1987; *Maekawa and Brown*, 1991]. Another model suggests that the western and eastern parts of the southern Coast Belt were part of the same Jurassic arc system that was duplicated by major Early Cretaceous sinistral faulting [*Monger et al.*, 1994]. Our study does not favor a single

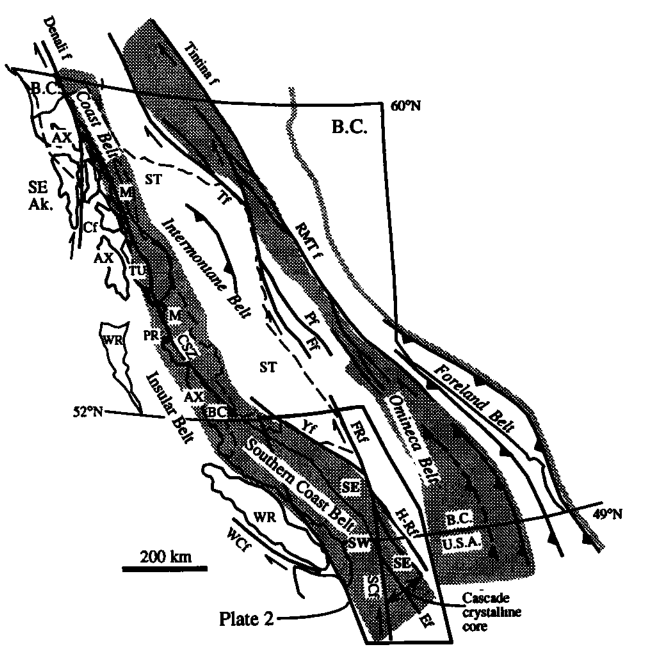


**Figure 1.** Regional tectonic setting of the Coast Belt of NW Washington, British Columbia, and SE Alaska showing other geophysiographic belts, major terranes, mid-Cretaceous thrust systems outside the southern Coast Belt, and Late Cretaceous to early Tertiary dextral, strike-slip faults. Abbreviations are AX, Alexander terrane; BC, Bella Coola; Cf, Chatam Strait fault; CSZ, Coast Shear Zone; Ef, Entiat fault; Ff, Finlay fault; FRf, Fraser fault; H-Rf, Hozameen and Ross Lake faults; M, unassigned metamorphic belt; Pf, Pinchi fault; PR, Prince Rupert; RMTf, Rocky Mountain Trench fault; SCf, Straight Creek fault; bold SE, southeastern Coast Belt; ST, Stikine terrane; bold SW, southwestern Coast belt; Tf, Teslin fault; TU, Taku terrane; WCf, West Coast fault; and WR, Wrangellia terrane. Map is compiled after *Wheeler et al.* [1991], *Rubin et al.* [1990], *Journeay and Friedman* [1993], *Evenchick* [1991], and *Gabrielse* [1985].

model, but we conclude that plate-boundary changes and/or conditions are important in explaining the thrust system because of its great length and width.

The primary difficulties in analyzing the mid-Cretaceous thrust system in the southern Coast Belt are the lack of a coherent stratigraphy in much of the belt and the presence of the major dextral, strike-slip faults of latest Cretaceous and early Tertiary age that disrupted the thrust system (Plate 1). The wealth of new research in the past decade on these strike-slip faults, mid-Cretaceous thrusts and folds, correlations of rock units, and crustal structure based on seismic reflection data allows us to better analyze the thrust system.

In this paper, we present two reconstructions of the strike-slip faults (Plate 2 and Figure 2), and use these to analyze the style, spatial relations, and timing of thrusting in the southern Coast Belt. We favor one (Plate 2) [after *Umhoefer and Schiarizza,* 1996] that nicely reconciles apparent contradictions within the strike-slip fault system. We also make an explicit effort to tie together thrust faults from the southern Coast Mountains of British Columbia to the North Cascades of Washington, two areas that were linked together early [e.g., *Crickmay,* 1930] but have not always been viewed as the same belt . We feel this synthesis of the reconstructed southern Coast Belt makes a sensible, coherent pattern out of what often seems to be an inscrutable collage. We also briefly explore the relation of thrusting and magmatism in the southern Coast Belt. It has been increasingly recognized that plutons in many arcs were emplaced during regional contraction [e.g., *Hutton and Reavy,* 1992, *Miller and Paterson,* 1992; *Tobisch et al.,* 1995], but thrust belts in magmatic arcs are less well studied in comparison to foreland fold-and-thrust belts, where the now classic relationships of folds to faults and fault geometry were described [e.g., *Dahlstrom,* 1969; *Boyer and Elliot,* 1982; *Suppe,* 1983]. In addition, none of the previously described contractional arcs have such a wide thrust system exposed at different crustal levels as in the thrust system reported here in the southern Coast Belt.

## Cretaceous Tectonic Setting of Southern Coast Belt

The southern Coast Belt includes the Wrangellia terrane along the western edge and terranes of the Intermontane superterrane along the eastern margin and to the east (Figure 1). Making up most of the southern Coast Belt are numerous small terranes that had a complex late Paleozoic to Mesozoic history before accreting to North America in Jurassic to Cretaceous time (Table 1) [e.g., *Monger and Journeay,* 1994]. We include the Coast Mountains of SW British Columbia and the North Cascades of Washington in the Coast Belt. Historically, these two regions were separated, because the western parts of these ranges have substantially different geology at the surface. We note, however, following others [*Crickmay,* 1930; *Misch,* 1966; *Monger et al.,* 1982], that the geology of the eastern parts of both regions has much in common and that one Mesozoic terrane in the western part of the Coast Belt in SW British Columbia is exposed in a thrust window in the northwestern Washington Cascades (Plate 1). These relationships strongly suggest that the western block in British Columbia structurally underlies much of northwestern Washington.

Herein we commonly use three terms for geologic/physiographic divisions of the Coast Belt. We use southern Coast Belt to refer to that part of the Coast Belt south of 52°N (Figure 1). This usage is both geologically sensible and practical because there have been many studies in the Coast Belt south of Bella Coola but fewer recent studies from there to the Prince Rupert region (Figure 1). Geologically, the region south of 52°N includes the Tyaughton - Methow basins on the northeast and the NW Cascades - San Juan Islands belt on the southwest and numerous terranes, all of which have no counterpart north of 52°N. We further divide the southern Coast Belt into

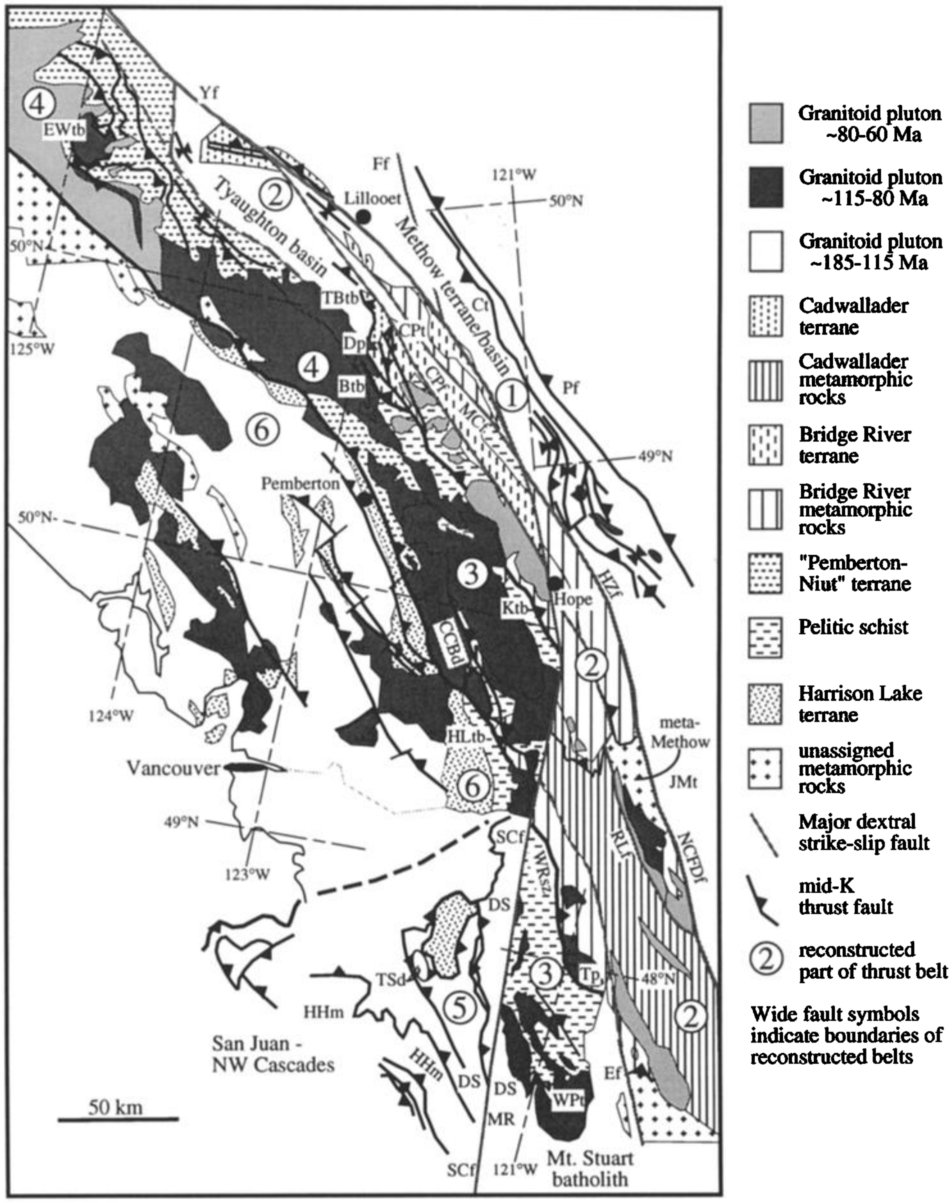


**Figure 2.** Reconstruction B: a reconstruction of the southern Coast Belt using the offset and timing on major dextral slip faults in Table 3. See text for discussion. Unit designations and abbreviations are as in Plates 1 and 2. Thin dashed lines are present lines of latitude and longitude for reference.

two tectonic domains following *Monger and Journeay* [1994], the southwestern and southeastern Coast Belt (Figure 1 and Plate 1). The Northwest Cascades do not neatly fit this scheme; we choose to include them in the southwestern Coast Belt because it is geographically sensible and they contain local exposures of rocks similar to the southwestern belt of British Columbia, but they also include rocks potentially correlable to rocks of the southeastern belt.

## Rock Units

The older rocks of the southwestern Coast Belt include the Wrangellia and Harrison Lake terranes in British Columbia (Table 1, Plate 1). Voluminous plutonic rocks intrude these terranes (Table 1, Plate 1), which were linked by ~165 Ma by a suite of similar plutons [*Mahoney,* 1994; *Friedman and Armstrong,* 1995]. The southwestern Coast Belt in Washington (Northwest Cascades and San Juan

**Table 1.** Summary of Major Rock Units in the Southern Coast Belt

| Rock Unit | Age | Description | Refer- ence |
|---|---|---|---|
| Methow terrane | M-U Jurassic | volcanic rocks and overlying sandstone and mudstone | 1,2,3 |
| | L Jurassic | deep marine sandstone and shale | 2, 3 |
| | Triassic | oceanic basalt | 4 |
| Methow basin | UCretaceous | nonmarine red beds and andesites | 5 |
| | L Cretaceous | marine clastic rocks | 5,6,7 |
| Cadwallader terrane (Cascade River unit) | L-M Jurassic | shallow to deep marine sandstone and shale | 8 |
| | U Triassic | volcanic arc and shallow marine and nonmarine sandstone and limestone | 9, 10 |
| | Permian | ophiolite complex, serpentinite melange | 11,12 |
| Tyaughton basin | UCretaceousL | nonmarine conglomerate and andesites | 13 |
| | Cretaceous | marine clastic rocks-complex facies | 13 |
| | MU Jurassic-L Cretaceous | shallow marine to marginal marine sandstone, siltstone and conglomerate | 14 |
| Bridge River terrane (Cogburn Group, Napeequa unit, Elbow Lake Formation, Deadman Bay unit) | Miss. to U Jurassic | oceanic rocks: argillite, chert, basalt, and minor sandstone, limestone, ultramafite | 15,111 6,12 |
| Stikine terrane | L Cretaceous | conglomerate, sandstone | 17,18 |
| | M Jurassic | volcanic arc, in south only | 19 |
| | U Triassic | volcanic arc and clastic rocks | 20,18 |
| Pelitic schist (Chiwaukum schist, Settler schist, Chism Schist, Cayoosh assemblage) | Triassic ??? Jurassic ??? L Cretaceous | Pelitic schist, lesser psammitic schist, amphibolite and ultramafite | 21 |
| Harrison Lake terrane | L Cretaceous | sandstone and volcanic rocks | 22 |
| | M-U Jurassic | volcanic arc and sandstone and shale | 22 |
| | U Triassic | clastic rocks | 22 |
| Darrington phyllite/ | U Jurassic | phyllite and greenstone and blueschist | 23 |
| Shuksan Greenschist | L Cret. ?? | | 24 |
| Helena-Haystack melange (Manastash unit) | U Jurassic - Cretaceous | serpentinite matrix with blocks of ophiolitic rocks, tonalite, amphibolite, felsic metavolcanic, and sandstone | 25 |
| Ingalls Complex | U Jurassic | ophiolitic complex | 26 |
| Swakane terrane | Proterozoic? Paleozoic? | biotite gneiss | 12,27 |

1, *Mahoney*, [1994]; 2, *Coates*, [1974]; 3, *O'Brien*, [1986]; 4, *Ray*, [1986]; 5, *McGroder*, [1989]; 6, *Trexler*, [1985]; 7, *Barksdale*, [1975]; 8, *Umhoefer and Tipper*, [1996]; 9, *Rusmore*, [1987]; 10, *Umhoefer*, [1990]; 11, *Schiarizza et al.*, [1996]; 12, *Tabor et al.*, [1989]; 13, *Garver*, [1989, [1992]; 14, *Umhoefer*, [1989]; 15, *Potter*, [1986]; 16, *Cordey and Schiarizza*, [1993]; 17, *Umhoefer et al.*, [1994]; 18, *Journeay and Freidman*, [1993]; *Riddell*, [1991]; 19, J.M. Journeay, (pers. comm., 1994); 20, *Rusmore and Woodsworth*, [1991b]; 21, *Plummer*, [1980]; *Mahoney and Journeay*, [1993]; 22, *Arthur et al.*, [1993]; *Mahoney et al.*, [1995]; 23, *Misch*, [1966]; 24, *Brown*, [1987]; 25, *Tabor*, [1994]; 26, *Miller*, [1985]; 27, *Rasbury and Walker*, [1992].

Islands) is a region dominated by various oceanic and arc terranes and lacking plutons (Table 1, Plate 1) [*Misch,* 1966; *Brown,* 1987; *Brandon et al.,* 1988].

To the east, the southeastern Coast Belt consists of a group of terranes of arc and oceanic affinity distributed in an elongate fashion: Cadwallader, Bridge River, Methow terranes, and a Pelitic belt (Table 1 and Figure 2). Overlying the Cadwallader and Methow terranes are late Middle Jurassic and early Late Cretaceous marine clastic and volcanic strata of the Tyaughton - Methow basin (Plate 1) [*Jeletzky and Tipper,* 1968; *Coates,* 1970; *Barksdale,* 1975; *Kleinspehn,* 1985; *Glover et al.,* 1988; *Garver,* 1992; *Mahoney,* 1992]; the Bridge River terrane is only demonstrably overlain by mid-Cretaceous clastic rocks [*Garver,* 1992]. *Garver* [1992] and *McGroder* [1989] have argued that the uppermost Lower Cretaceous (mid-Albian, ~105-100 Ma) strata were deposited in front of active thrusts [*Trexler,* 1985].

The northeastern part of the Cascades core (the area between the White River shear zone on the southwest and the Ross Lake fault to the northeast, Figure 2) is a Cretaceous and Paleogene plutonic and metamorphic belt that has commonly been considered a separate entity than the Coast Belt in SW British Columbia. In recent years, however, it has been proposed that most of the metamorphic rocks are equivalent to the lower-grade Cadwallader and Bridge River terranes [*Monger,* 1986; *Tabor et al.,* 1989; *Miller et al.,* 1993a], and we thus assign the Cascade core to the southeastern belt. One possible exception to this assignment is the enigmatic Swakane terrane, which is a monotonous sequence of largely biotite gneiss that may be a displaced fragment of Paleozoic or Proterozoic crust [e.g., *Haugerud et al.,* 1994].

Much of the southeastern Coast Belt in British Columbia has been intruded by only scattered plutons, which in general are younger to the east [*Friedman and Armstrong,* 1995]. Mid-Cretaceous plutons are widely distributed across the region (Plate 1) [*Friedman and Armstrong,* 1995]. The latest Cretaceous to early Tertiary plutonic belt is solely in the east.

## Structural Geology

Virtually the entire southern Coast Belt is cut by a complex thrust system with both northeast and southwest dipping thrusts; northeast dipping thrusts are the dominant structure (Plate 1) [*Misch,* 1966; *Tabor et al.,* 1987, 1989; *Brandon et al.,* 1988; *Brown,* 1987; *Miller and Paterson,* 1992; *Journeay and Friedman,* 1993]. However, the dip and density of thrusts vary greatly throughout the belt. Crustal-scale seismic reflection profiles across the southern Coast Belt are interpreted to define many kilometer-scale tectonic wedges bounded by both northeast and southwest dipping thrusts in the southeastern Coast Belt [*Varsek et al.,* 1993]. U-Pb zircon data from synthrusting and postthrusting plutons [*Journeay and Friedman,* 1993; *Rusmore and Woodsworth,* 1994; *Paterson et al.,* 1994] indicate that thrust faulting occurred from 97 to ~80 Ma. Structural and stratigraphic relations in the basins on both sides of the Coast Belt suggest that thrusting began ~105-100 Ma (mid-Albian) and lasted until ~85-80 Ma [*Brandon et al.,* 1988; *McGroder,* 1989; *Garver,* 1989; *Umhoefer,* 1989]. An exception to this time of termination is the narrow region of major dextral, strike-slip faults in the southeastern domain, where local thrust faulting was commonly associated with strike-slip faulting [*Journeay et al.,* 1992; *Schiarizza et al.,* 1990; *Miller and Bowring,* 1990], and in eastern parts of the Cascades core where contraction continued until at least 72 Ma [*Paterson and Miller,* 1995]. Where relations can be demonstrated, southwest vergent thrust faulting always began before northeast vergent faulting and outlasted it [*McGroder,* 1989; *Schiarizza et al.,* 1990].

The southwestern Coast Belt in British Columbia consists of widely spaced, northeast dipping, thrust faults cutting abundant plutonic bodies and low-grade rocks of the Wrangellia and Harrison Lake terranes [*Monger,* 1990; *Journeay and Friedman,* 1993]. The southwestern belt in Washington is the northwest Cascades - San Juan Islands thrust belt [*Misch,* 1966; *Brandon et al.,* 1988; *Brown,* 1987], which includes diverse low-grade thrust sheets, with no synthrusting plutons, that were thrust over the Wrangellia and Harrison Lake terranes [*Brandon et al.,* 1988]. The southeastern Coast Belt in British Columbia contains a narrow zone of medium- to high-grade rocks of the Stikine terrane, Bridge River terrane, and Settler Schist [*Journeay and Friedman,* 1993]. These rocks are cut by a complex system of ductile thrust faults and intruded by numerous synthrusting and postthrusting plutons. Metamorphic grade increases across strike (structurally upward) to the east and decreases along strike to the northwest [*Journeay and Friedman,* 1993]. The southern extension of these thrusts in Washington in the Cascades core is an area of metamorphic rocks that record multiple generations of folds, penetrative foliation and mineral lineation, and local ductile thrust shear zones [e.g., *Misch,* 1966; *Brown and Talbot,* 1989; *Miller and Paterson,* 1992; R.B. Miller and S. R. Paterson, unpublished data, 1995]. The bulk of the southeastern Coast Belt lies to the east of the high-grade rocks and consists of low-grade slices of the Cadwallader, Bridge River, and Methow terranes and strata of the Tyaughton - Methow basin [*Schiarizza et al.,* 1990; *Journeay and Friedman,* 1993]. These rocks are cut by both northeast and southwest dipping thrusts.

A major system of dextral, strike-slip faults cut the southeastern Coast Belt from ~80 to ~40 Ma (Plate 1) [*Monger,* 1985; *Kleinspehn,* 1985; *Miller and Bowring,* 1990; *Umhoefer and Schiarizza,* 1996]. These structures were used in our reconstructions. This strike-slip faulting was probably caused by dextral-oblique subduction of the Kula plate beneath North America [*Engebretson et al.,* 1985].

## Was the Southern Coast Belt a Coherent Block in Mid-Cretaceous Time?

Our reconstructions result in the southern Coast Belt forming a coherent block with many throughgoing belts (Plate 2). Paleomagnetic data also suggest the block was contiguous during the mid-Cretaceous, not widely separated into smaller blocks.

**Table 2.** Fault Scenario Used for Reconstruction A

| Stage of Faulting | Total Offset | Offset on Individual Faults |
|---|---|---|
| Mid-late Eocene ~44 - >34 Ma | 110 km | 110 km, Straight Creek fault (South)<br>100 km, Fraser River fault (North)<br>10 km, Marshall Creek/NW Yalakom fault (North) |
| Middle Eocene ~47 - 44 Ma | 50 km | 50 km, Straight Creek fault<br>30 km, N-S closing of NE core of North Cascades<br>20 km, Marshall Creek/NW Yalakom faults |
| Early Eocene ~58 - ~47 Ma | 85 km | 85 km, Yalakom/Hozameen/Foggy Dew faults |
| Latest Cretaceous - Paleocene ~80 - 60 Ma | 10 km | 10 km, Castle Pass/Downton Creek/Ross Lake faults |
| | (255 km total) | |

Paleomagnetic data from the southern Coast Belt suggest that it may have moved northward 2500 - 3000 km after ~90 Ma. If parts of the block moved northward >600 km more than other parts (the strike length of the southern Coast Belt), then the block would have been in separate pieces in mid-Cretaceous time. However, results of paleomagnetic studies from four widely spaced locations within the southern Coast Belt (Plate 1) containing 90±10 Ma rock units all have similar northward translation within error, which suggests that the southern Coast Belt was contiguous: Mt. Stuart batholith, 3100±600 km [*Beck et al.*, 1981]; Spuzzum pluton, 2300±700 km [*Irving et al.*, 1985]; Porteau pluton, 3200±500 km or 1600±400 km [*Irving et al.*, 1995]; Silverquick Formation/Powell Creek volcanics, 3000±500 km [*Wynne et al.*, 1995] (Plate 1). The Silverquick/Powell Creek study is the only one done in layered rocks with unambiguous paleohorizontal. These results suggest that the block was coherent and that if a large-offset fault zone is present, it is east of the southern Coast Belt .

## Strike-Slip Fault Reconstructions for 80 Ma

In order to analyze the thrust system, we must first reconstruct the major dextral, strike-slip faults, which was done in two ways (Tables 2 and 3, Plate 2, Figure 2). Reconstruction A is based on a recent analysis of strike-slip faulting in the southeastern Coast Belt by *Umhoefer and Schiarizza* [1993, 1996] (Table 2, Plate 2). Reconstruction A is original in that it (1) accounts for a new, refined estimate of timing and displacement on the Yalakom and related faults, (2) incorporates the conclusions of *Coleman and Parrish* [1991] on the timing and kinematics of the Yalakom and Mission Ridge faults and their relation to other faults, (3) includes recent conclusions on the Ross Lake fault [*Miller*, 1994], (4) accounts for penetrative extension in part of the Cascade core [*Haugerud et al.*, 1991], and (5) resolves an outstanding conflict in the timing and offset of the Fraser and Straight Creek faults, segments of the same fault zone.

Reconstruction A has the following history [from *Umhoefer and Schiarizza,* 1996] (Table 2, Figure 3). From ~85 to ~58 Ma, the Ross Lake - Downton Creek - Castle Pass faults were one zone that had 10 km of dextral offset (Figure 3b). Dextral, strike-slip, and thrust faulting (the latter not accounted for in the reconstruction) were also occurring at the same time in this zone and northeast of the Entiat fault [*Hurlow*, 1993; *Paterson and Miller,* 1995]. This transpressive stage of deformation ended about 60-57 Ma, near the end of the Paleocene, when a dextral + extensional stage began accompanied by widespread development of basins within the Coast Belt, which are conspicuously absent in the latest Cretaceous to Paleocene stage. This second stage from ~58 to 47 Ma saw ~80 km of dextral slip on the Yalakom fault and subsidiary faults and related extension on the Tatla Lake metamorphic core complex [*Friedman and Armstrong,* 1988] (Figure 3c). The Hoza-

**Table 3.** Fault Scenario Used for Reconstruction B

| Stage of Faulting | Total Offset | Offset on Individual Faults |
|---|---|---|
| Mid-late Eocene ~44 - >34 Ma | 100 km | 100 km, Straight Creek fault (South)<br>90 km, Fraser River fault (North)<br>10 km, Marshall Creek/NW Yalakom fault (North) |
| Middle Eocene ~47 - 44 Ma | 20 km | 20 km, Marshall Creek/NW Yalakom faults |
| Early Eocene ~58 - ~47 Ma | 85 km | 85 km, Yalakom/Hozameen/Foggy Dew faults |
| Latest Cretaceous - Paleocene ~80 - 60 Ma | 10 km | 10 km, Castle Pass/Downton Creek/Ross Lake faults |
| | (215 km total) | |

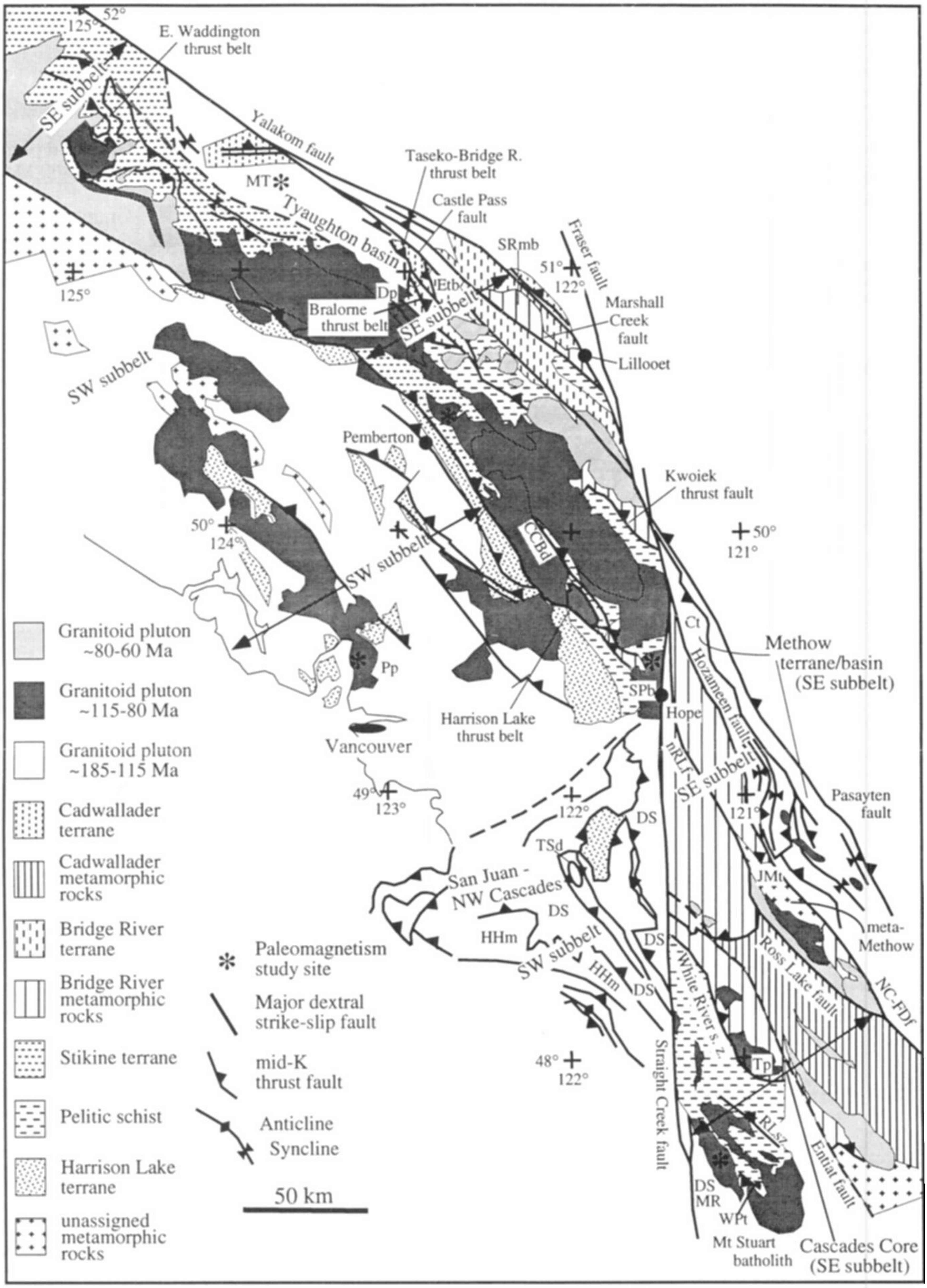


**Plate 1.** Geologic map of the southern Coast Belt (52° to 47°N) showing major lithotectonic belts, mid-Cretaceous thrust belts, and major early Tertiary dextral, strike-slip faults. The Pasayten fault is shown as a thrust fault following the interpretation of *Varsek et al.* [1993]. Abbreviations are CCBd, central Coast Belt detachment; Ct, Chuiwaunten thrust fault; Dp, Dickson Peak pluton; DS, Darrington - Shuksan units; Etb, Eldorado thrust belt; HHm, Helena-Haystack melange; JMt, Jack Mountain thrust; MR, Manastash Ridge; MT, Mount Tatlow; NC-FDf, North Creek - Foggy Dew fault; nRLf, north Ross Lake fault; Pp, Porteau pluton; SPb, Spuzzum batholith; RLsz, Rock Lake shear zone: SRmb, Shulaps Range metamorphic belt; Tp, Tenpeak pluton; TSd, Twin Sisters dunite; WPt, Windy Pass thrust. Map is compiled from *Tabor et al* [1987, 1993, 1994], *McGroder* [1989], *Rusmore and Woodsworth* [1994], *Schiarizza et al.* [1993], *Journeay et al.* [1992], and *Journeay and Friedman* [1993].

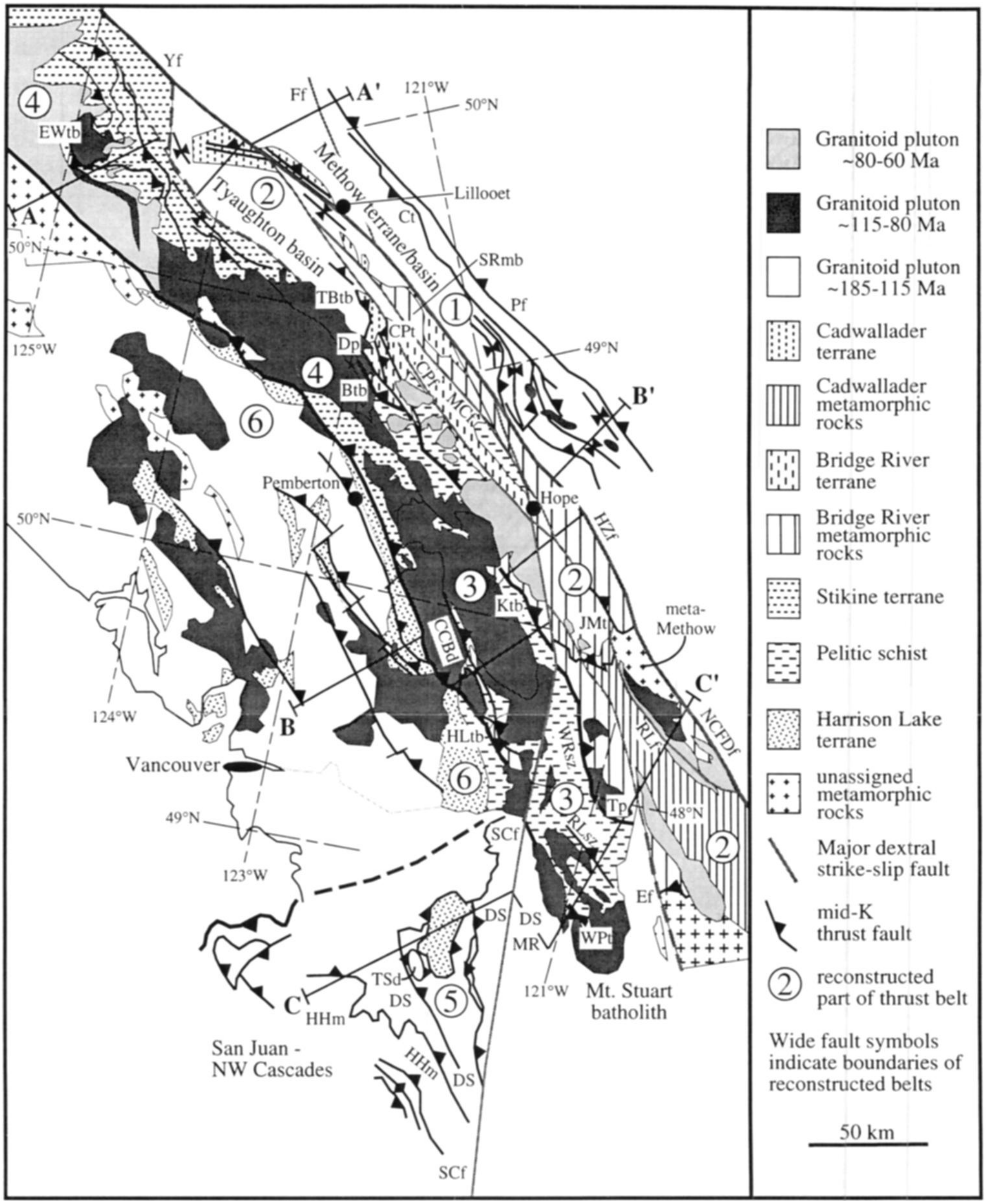


**Plate 2.** Reconstruction A: our preferred reconstruction of the southern Coast Belt using the offset and timing on major dextral slip faults in Table 2 after *Umhoefer and Schiarizza* [1996]. See text for discussion. Unit designations and abbreviations are as in Plate 1; additional abbreviations are Btb, Bralorne thrust belt; CPf, Castle Pass fault; CPt, Castle Pass thrust, EWtb, eastern Waddington thrust belt; Ef, Entiat fault; Ff, Fraser fault; HLtb, Harrison Lake thrust belt; HZf, Hozameen fault; Ktb, Kwoiek thrust belt; MCf, Marshall Creek fault; NCFDf, North Creek-Foggy Dew fault; Pf, Pasayten fault; RLf, Ross Lake fault; RLsz, Rock Lake shear zone: SCf, Straight Creek fault; TBtb, Taseko-Bridge River thrust belt; WRsz, White River shear zone; Yf, Yalakom fault. Thin dashed lines are present lines of latitude and longitude for reference.

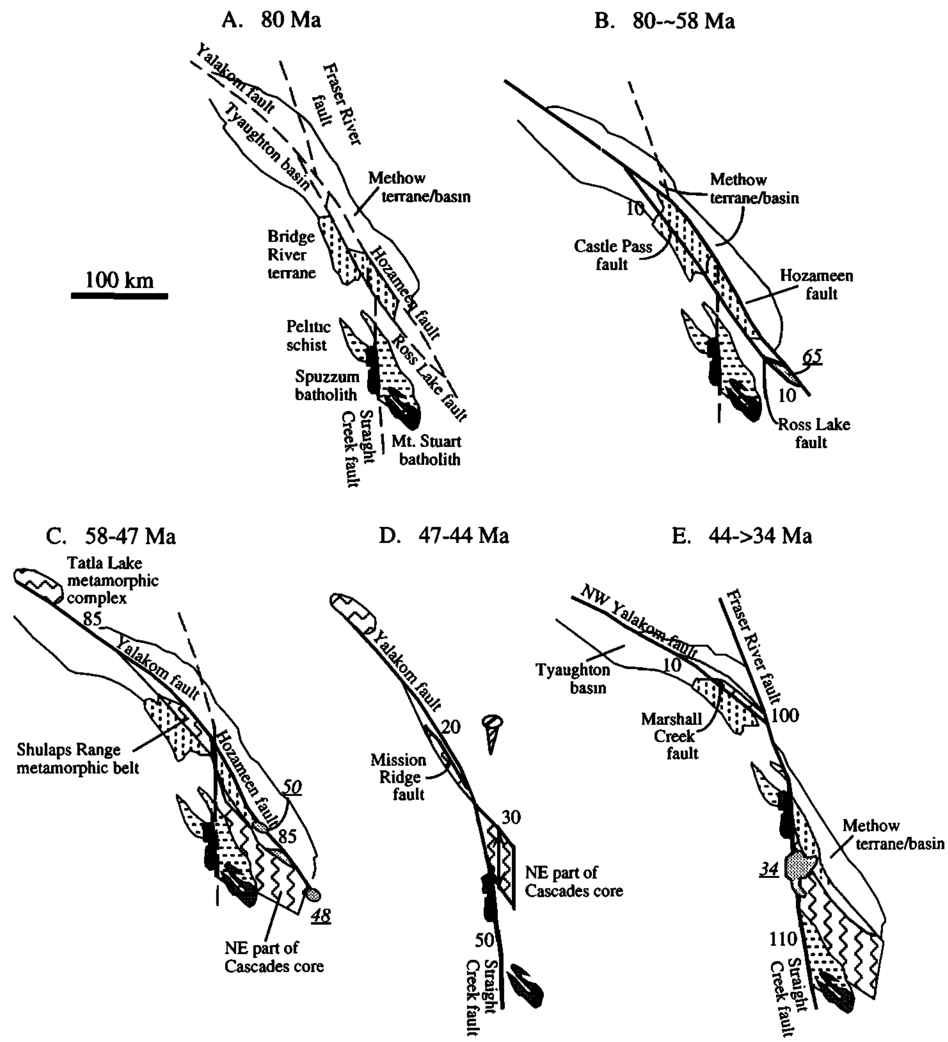


**Figure 3.** A five-step sequential map-view depiction of reconstruction A (after *Umhoefer and Schiarizza,* 1996). A few of the major geologic features of the southern Coast Belt are shown for reference with patterns like Plate 2, except for the vertical chevron pattern, which indicates regions where middle crustal rocks were deformed and later uplifted within the Eocene. Thin long dashed lines are faults that move after the particular stage of the reconstruction; wide solid lines are faults that were active during that stage; thin solid lines are faults that were inactive by that stage. Large numbers next to active faults are the amount of dextral offset in kilometers restored during that stage; large underlined numbers are the radiometric age of the adjacent pluton that gives constraints on age of faulting. The large screw in Figure 3d is to help visualize that if that block is relatively stable, then the amounts of offset in the Skagit part of the Cascades core, Straight Creek fault, and Yalakom fault are compatible (that is, Straight Creek offset = Yalakom + Skagit offset).

meen fault was probably the major southern extension of the Yalakom, although the Ross Lake fault may have been active as well with lesser offset [*Miller,* 1994]. At 47 Ma, the system changed as movement on most of the Ross Lake and the Hozameen faults died, the Straight Creek fault began activity in the south and the Marshall Creek fault became a link between the Straight Creek and NW Yalakom fault in the north (Figure 3d). From ~47 to 44 Ma, this new Straight Creek - Marshall Creek - Yalakom fault system was the major dextral fault zone and accounted for ~20 km of dextral offset. Adjacent to, and below, this major upper crustal strike-slip fault zone, the Shulaps Range and northeastern part of the Cascades core were evolving from broad mid and lower crustal (respectively) dextral shear zones to unroofing metamorphic complexes bounded by oblique and normal slip brittle faults [*Coleman and Parrish,* 1991; *Haugerud et al.,* 1991]. The transtension and unroofing of the Cascades core are interpreted to involve ~30 km of N-S extension in this reconstruction; this accounts for another 30 km of offset on the Straight

Creek fault that did not occur on the northern faults. The final stage of strike-slip activity from 44 to 34 Ma began with a "Y" configuration as the Fraser fault began activity as the major northern extension of the Straight Creek fault and offset of 10 km continued on the Marshall Creek - Yalakom fault system (Figure 3e). Deformation soon shifted solely to the Straight Creek - Fraser fault system, which accumulated 110 and 100 km of offset, respectively, during this stage.

The contrast between reconstructions A and B is in the interpretations of the Straight Creek fault. Reconstruction B uses the alternate interpretation of 90 - 100 km of dextral slip on that fault (Table 3, Figure 3). The Straight Creek fault does not have an early history independent of the Fraser fault in this model, and therefore the two faults have 100 and 90 km of offset, respectively (10 km is still transfered from the Straight Creek to Marshall Creek fault). In addition, in this reconstruction no significant extension occurs in the Skagit part of the Cascades core.

Our two reconstructions do not incorporate two different interpretations of the Fraser fault. *Friedman and van der Heyden* [1992] demonstrated that two plutons now separated ~140-160 km across the Fraser fault have a similar Permian age. We note that the rock units surrounding the two plutons are very different and these plutons and the rocks surrounding them have experienced multiple deformations. Thus the validity of a simple match across the Fraser fault is questionable. *Monger and Journeay* [1994] use 125 km of offset on the Fraser fault, based on matching the Yalakom and Ross Lake faults, belts of Eocene extension and plutonism [*Coleman and Parrish,* 1991], and latest Cretaceous plutons. We note, however, that the belt of Eocene extension and plutonism is wide enough that it is still a coherent, though more elongate, belt using our 100 km offset on the Fraser fault. In summary, we favor the offset on the Fraser fault that makes the belts of geology in the Cretaceous, before the strike-slip faulting, the most coherent, and that is ~90-100 km of offset on the Fraser fault [*Monger*, 1985].

### Local Thrust Fault Relations

**Eastern Waddington thrust belt.** Thrust faults in this belt cut Triassic volcanic and sedimentary rocks assigned to the Stikine terrane and a volcanic unit and overlying clastic unit of Early Cretaceous age [*Rusmore and Woodsworth,* 1994; *Umhoefer et al.,* 1994]. The northeastern front of the thrust belt also cuts the Albian Taylor Creek Group and Upper Cretaceous Powell Creek volcanics. Ages from synthrusting and postkinematic plutons and metamorphic patterns indicate that thrusting began by 87-84 Ma and, ended soon after and the area cooled steadily into the early Tertiary [*Rusmore and Woodsworth,* 1994]. The presence of the Taylor Creek Group in the foreland of the belt suggests thrusting began in Albian time, about 110-100 Ma, because that unit is synorogenic in its type area ~100-150 km to the southeast [*Garver*, 1992].

The eastern Waddington thrust belt (Figure 4, A'A') is a coherent group of northwest striking and southwest dipping thrusts that displace low-grade to unmeta-morphosed rocks in the northeast and mid amphibolite facies metamorphic rocks in the southwest [*Rusmore and Woodsworth,* 1994]. A well-developed schistosity and downdip elongation lineation formed during the main phase of deformation. Northeast vergent, late-stage map-scale folds, small-scale structures, and map relations all indicate top-to-the-northeast thrusting. Shortening across the thrust belt was at least 50% (~40 km) but may have been significantly more as this estimate is only from the frontal part of the belt [*Rusmore and Woodsworth,* 1994].

**Taseko Lake - Bridge River and Bralorne - Kwoiek Creek thrust belt.** The Taseko Lakes - Bridge River and Bralorne - Kwoiek thrust belts (Plate 1) are contiguous and show similar structural histories [*Schiarizza et al.,* 1990; *Journeay et al.,* 1992]. The region also experienced periodic and spatially discontinuous magmatism in latest Cretaceous and early Tertiary time, but there are no plutons of mid-Cretaceous age, the age of most of the thrusting. The complex faulting can be divided into three stages, only the first of which is relevant to our analysis here: southwest and northeast vergent thrusting and associated folding from 96 Ma (or as early as ~105 Ma) to ~86 Ma; oblique dextral-thrust and dextral faulting between 86 and 68 Ma; and dextral and extensional faulting in Paleocene (?) and Eocene time [*Schiarizza et al.,* 1990; *Journeay et al.,* 1992]. The pre-86 Ma thrusts form two main systems. The Bralorne system consists of anastomosing, moderately to gently northeast dipping faults that show southwest directed motion based on small-scale structures. This thrust system cuts rocks as young as the Albian Taylor Creek Group and is locally overlain by ~90-80 Ma volcanic rocks and truncated by the 92 Ma Dickson Peak pluton (Plate 1) [*Journeay et al.,* 1992]. The Eldorado system of thrusts is moderately southwest dipping, shows widespread evidence for northeast directed motion, and cuts faults of the Bralorne thrust system. These late-stage thrusts are interpreted to have been active during gold mineralization in the Bralorne district, where veins are 91 to 86 Ma [*Leitch et al.,* 1991]. In the Bralorne to Kwoiek area, this thrust system separates rocks with polyphase deformation in the western footwall from rocks with one episode of deformation in the hanging wall, and therefore these thrusts are out-of-sequence relative to the Harrison Lake belt discussed below [*Journeay et al.,* 1992].

**Harrison Lake thrust belt.** The western part this belt is cut by widely spaced northeast dipping thrust faults of the foreland that have brittle-ductile character and downdip lineations (Plate 2 and Figure 4, B-B') [*Journeay and Friedman,* 1993]. Thrusts of an imbricate zone (on the boundary of the southwestern - southeastern Coast Belt) are low angle with mylonites and downdip stretching lineations, and they expose high-grade metamorphic rocks [*Journeay and Friedman,* 1993]. Kinematic indicators in the west consistently indicate top-to-the-southwest motion. This thrusting is the early stage of a two-stage history and was active after eruption of 102 Ma volcanic rocks, during intrusion of a 97 Ma pluton, and before intrusion of a 96 +6/-5 Ma pluton [*Journeay and Friedman,* 1993]. The steeply northeast dipping, ductile central Coast Belt detachment is a major late-stage reverse fault that separates the imbricate zone from the eastern part of the thrust belt

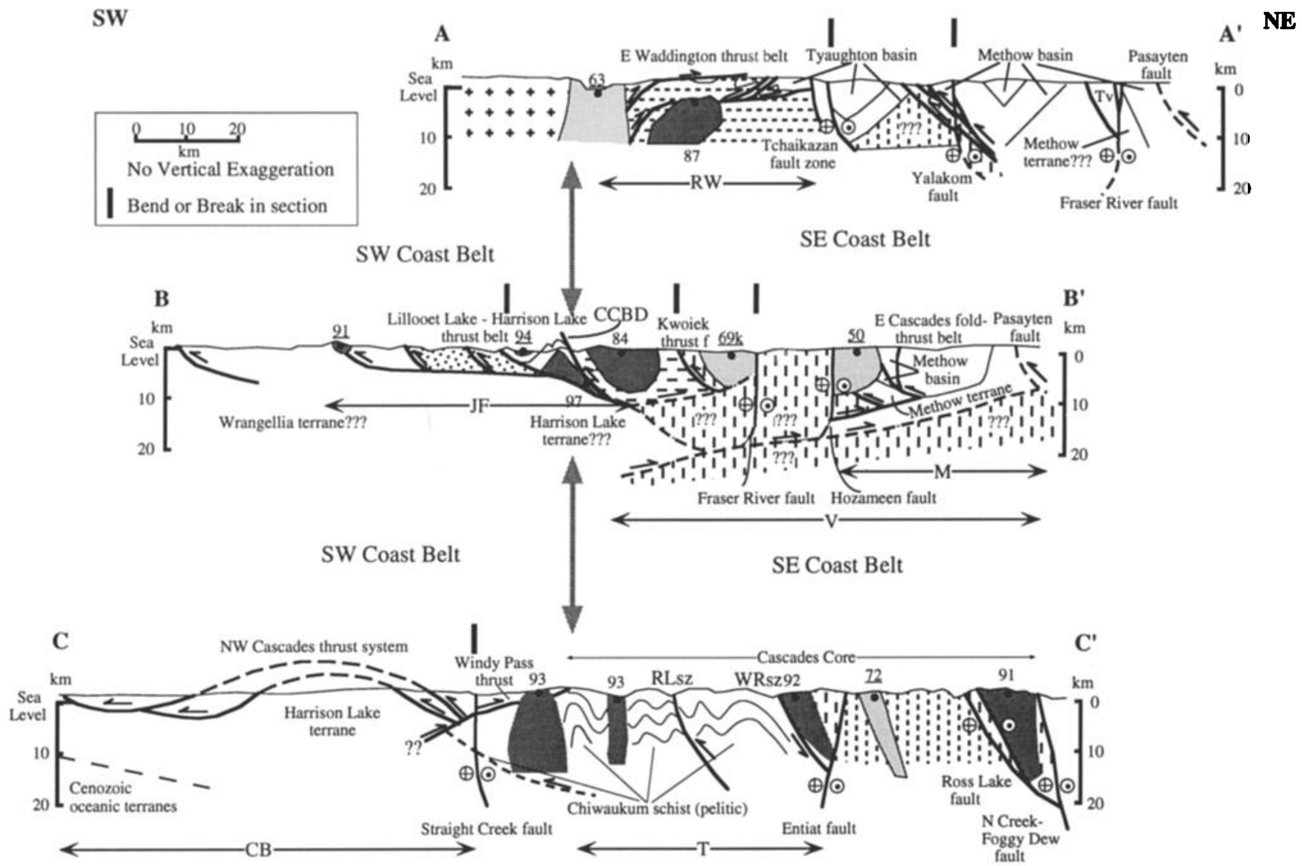


**Figure 4.** Cross sections from the northern (A-A'), central (B-B'), and southern (C-C') portions of reconstruction A (Plate 2). Part of section A-A' is from *Rusmore and Woodsworth* [1994], (RW), part of section B-B' is from *Journeay and Friedman* [1993], (JF), *McGroder* [1989], (M), and *Varsek et al.* [1993], (V), and part of section C-C' is from *Cowan and Bruhn* [1992], (CB), and *Tabor et al.* [1987], (T). Short dashed lines are taken directly or conceptually from the interpretations from seismic reflection data [*Varsek et al.*, 1993]. Patterns are same as Plates 2, 3, and Figure 2. Thin lines with no patterns are bedding in A-A' and foliation in C-C'. Numbers above dots in sections are ages of the displayed plutons: underlined numbers are postthrusting plutons; others are synthrusting plutons. See Plate 2 for location of the sections.

[*Journeay and Friedman*, 1993]. Fabrics in mylonites along the detachment indicate east-side-up displacement. Structures in the high-grade hanging wall of the detachment include early tight folds and late folds overturned to the southwest. Late-stage structures are synkinematic with the detachment and demonstrate that the southeastern belt included a series of low-angle thrusts that were cut by higher angle faults. In the west, late and postkinematic plutons of the late stage are 94 and 91 Ma, and in the imbricate zone a postkinematic pluton is 94 +6/-5 Ma [*Journeay and Friedman*, 1993]. Thus thrusting in the Harrison Lake belt occurred in two stages from ~100 to ~90 Ma, similar to the southwest vergent thrusting of the Bralorne system.

**Eastern Cascades Fold belt.** This belt deforms the predominantly sedimentary rocks of the Methow basin into north to northwest trending, moderately to steeply dipping thrusts and gently plunging map-scale folds, which were active between ~ 100 and 88 Ma [*McGroder*, 1989]. The folds are open to generally tight and range from upright to overturned. Thrusts are east vergent in the northern part of the Methow basin, whereas west vergent thrusts may dominate in the southern part (eastern part of B-B' in Figure 4) [*McGroder*, 1989] (although *Haugerud et al.* [1994] state that evidence for the latter thrusts is equivocal). The largest structures are east vergent, the most important of which is the Chuwanten thrust, which puts Lower to Middle Jurassic Ladner Group on the Upper Cretaceous Pasayten Group [*McGroder*, 1989; *Monger and McMillan*, 1989]. *McGroder* [1989] utilized the regional southeast plunge of the Methow basin to construct balanced cross sections from which he interprets the overall structure of the basin as an east vergent tectonic wedge. McGroder has estimated that wedging resulted in ~ 50 km of ENE-WSW shortening near the international border, with shortening decreasing southward in the fold belt.

**Contractional structures in the southwestern part of the Cascades core.** The thrust belt in the southwestern part of the Cascades core (that part southwest of the Entiat fault, Plate 1) involves progressively deeper structural levels from SW to NE. The southern margin of the core is marked by the Windy Pass thrust, which carries ophiolitic rocks of the Middle to Late Jurassic Ingalls Complex of the Northwest Cascades System in its hanging wall [*Miller*, 1985]. Metamorphic grade in the Ingalls Complex increases from subgreenschist to amphibolite facies as this fault is approached. Ductile deformation intensifies near imbricate thrusts [*Miller*, 1985, 1988], and the Windy Pass thrust has been folded on the map scale. The vergence of the thrust is unknown, but regional relations are most compatible with the Ingalls Complex having originated to the south [*Miller et al.*, 1993b], and the fault possibly represents a northeast directed back thrust. Regardless of the vergence, the overlap of the Ingalls and the Chiwaukum Schist indicates a minimum displacement of 14 km [*Paterson et al.*, 1994]. The thrust was active between 96 and 93 Ma, but the age of initiation is uncertain [*Miller*, 1985; *Paterson et al.*, 1994].

The Chiwaukum Schist is the unit in the Cascades core that best preserves the mid-Cretaceous structures. It records at least five transposition cycles [*Paterson et al.*, 1994], most of which reflect regional progressive deformation marked by NE-SW contraction and synchronous NW-SE extension. Contraction is manifested by SW vergent folds that have gentle NW-SE trending fold axes and moderately NE dipping axial-planar cleavages and are associated with weak NW-SE trending stretching lineations [*Miller and Paterson*, 1992; *Paterson et al.*, 1994]. Most of this deformation occurred before and during emplacement of the 93 Ma Mount Stuart batholith. Latest recognized contractional structures in the southernmost part of the core are steep southwest-directed ductile shear zones that are synemplacement to postemplacement of the Mount Stuart [*Miller and Paterson*, 1992; *Magloughlin*, 1994]. These shear zones may mark significant breaks in metamorphic pressure within the Chiwaukum Schist [*Magloughlin*, 1994].

The Chiwaukum Schist records NE-SW shortening normal to the subhorizontal stretching lineation. *Brown and Talbot* [1989] interpreted the lineations in the Chiwaukum and elsewhere in the Cascades core to record pervasive orogen-parallel dextral shear. In contrast, others [*Miller and Paterson*, 1992; *Paterson et al.*, 1994; *Paterson and Miller*, 1995] have emphasized the lack of evidence for displacement parallel to this lineation. *Brandon et al.* [1994] have made a similar argument for lineations in the Northwest Cascades system, and we infer that the well-documented NE-SW contraction along the length of the Coast Belt [*Rubin et al.*, 1990] indicates that dextral shear was at most a minor compontent of the mid-Cretaceous deformation.

The Chiwaukum Schist experienced early low P/T metamorphism in the aureole of the Mount Stuart batholith and was subsequently loaded by up to 4 kbar [*Evans and Berti*, 1986; *Brown and Walker*, 1993; *Paterson et al.*, 1994]. This loading probably records emplacement of higher level mid-Cretaceous (~93-85 Ma) thrusts [*Evans and Berti*, 1986; *McGroder*, 1991; *Paterson et al.*, 1994], or possibly large plutons [*Brown and Walker*, 1993], over the Chiwaukum Schist. Thermobarometric data indicate that a major pressure gradient occurs in the southern part of the schist and presumably reflects either the thrust front or the boundary of the overlying pluton(s). The deepest structural levels (P ~ 9 kbar) in the northeastern part of the Chiwaukum Schist lie in the footwall to the White River shear zone (Plate 1) [*Magloughlin*, 1993; *Brown and Walker*, 1993]. This shear zone dips moderately to steeply north to NE, has a downdip lineation and reverse-slip kinematic indicators, and carries in its hanging wall the 91-92 Ma Tenpeak pluton and high pressure amphibolite-facies rocks of the Napeequa unit [*Van Diver*, 1967; *Tabor et al.*, 1987; *Magloughlin*, 1993]. The Napeequa is probably the high-grade correlative of the Bridge River terrane of the southeastern Coast belt [*Tabor et al.*, 1989; *Miller et al.*, 1993c, 1994]. The Tenpeak and several other mid-Cretaceous plutons in the hanging wall crystallized at high-pressures (7-9.5 kbar) [*Dawes*, 1993] in contrast to plutons of similar age elsewhere throughout the Cascades core, including the Mount Stuart batholith and other plutons that intrude the Chiwaukum Schist [*Miller et al.*, 1993a]. The involvement of the Tenpeak pluton and the retrograde metamorphism of the Chiwaukum Schist in the White River shear zone indicate that it postdates most of the contraction in the Chiwaukum Schist and movement on the Windy Pass thrust. Thus the shear zone is probably a major out-of-sequence structure. We also note that speculatively the shear zone flattens upward and was responsible for the loading of the Chiwaukum Schist to the southwest.

In summary, contraction in the southern part of the Cascades core is marked by repeated folding in the Chiwaukum Schist, movement on late reverse-slip shear zones, and possibly a major back thrust. Significant contraction began by 96 Ma, was active at 93 Ma and after 91 Ma, and ductile deformation ended by 80 Ma, based on the youngest K-Ar biotite ages [*Engels et al.*, 1976] in the schist near the White River shear zone [*Miller and Paterson*, 1992; *Paterson et al.*, 1994].

**Northeast Part of Cascades Core.** The most difficult part of the North Cascades in which to evaluate mid-Cretaceous contraction is in the Cascades core northeast of the Entiat fault (Plate 1). Much of the evidence there for mid-Cretaceous tectonics has been obscured by 75-45 Ma plutonism, metamorphism, and penetrative deformation [e.g., *Miller et al.*, 1989; *Haugerud et al.*, 1991]. The main manifestations of Cretaceous contraction are at least three cycles of approximately coaxial, generally SW vergent folds of gently to moderately dipping foliations [*Paterson and Miller*, 1995]. This folding in part occurred between 74 and 60 Ma [*Paterson and Miller*, 1995], but some of the earliest folds may record the mid-Cretaceous event. Other possible major mid-Cretaceous contractional structures include the pre-84 Ma folded, but generally gently dipping tectonic contact between the Swakane terrane (Table 1) and the overlying Napeequa unit [*Tabor et al.*, 1987; *Hurlow*, 1992] and Late Cretaceous or older inferred thrust boundaries between components of the Napeequa unit (probable metamorphosed Bridge River terrane) and

Cascades River unit (probable metamorphosed Cadwallader terrane) [e.g., *Brown et al.,* 1994].

**Northwest Cascades - San Juan Islands thrust system.** This system, which was active between ~ 100 and 84 Ma [*Brandon et al.,* 1988], is a thick stack of regional-scale low-angle nappes of mostly low-grade, late Paleozoic and Mesozoic arc-type and oceanic strata [*Misch,* 1966; *Monger,* 1966; *Brown,* 1987; *Brandon et al.,* 1988], which are thrust over Middle Jurassic to Lower Cretaceous strata that are probably the extension of the Harrison Lake terrane of the southwestern Coast belt (western part of C-C' in Figure 4) [*Misch,* 1966; *Monger and Journeay,* 1994]. Extending the thrust sheets west to the San Juan Islands is more difficult, although close similarities between San Juan units and rocks in the NW Cascades have been noted [e.g., *Brown and Vance,* 1987; *Brandon et al.,* 1988].

The thrusts commonly have shallow dips, but there are many exceptions. The overall map pattern suggests NW trending folds above ramps in a southwest or northeast vergent thrust system, but this pattern in part reflects Eocene and younger(?) folds [e.g., *Brandon et al.,* 1988; *Haugerud et al.,* 1994]. The thrusts formed at lower temperatures than those to the east in the Cascades core, as fault breccias, scaly fault-zone fabrics, and Riedel-type shear patterns are characteristic [*Cowan and Brandon,* 1994; *Haugerud et al.,* 1994]. Low-T (< 200°C), high-P metamorphism accompanied to slightly postdated thrusting and was presumably related to rapid structural burial and subsequent uplift within an advancing thrust wedge [*Brandon et al.,* 1988].

The kinematics of the thrust system are controversial. Southwest vergence is supported by the (1) regional northwest strike of the system, including the inferred foreland basin [e.g., *Brandon et al.,* 1988]; (2) brittle fault geometries [*Cowan and Brandon,* 1994]; (3) orientation of asymmetric folds [*Misch,* 1966; *Cowan and Brandon,* 1994]; and (4) evidence for southwest directed thrusting along strike to the northwest in the Coast Belt for ~ 1200 km [*Rubin et al.,* 1990]. *Misch* [1966] proposed a slightly different and more complex kinematic model with overturned folds and associated faults that record SE vergence on the south, western vergence near the International boundary, and NW vergence on the north [cf. *Crickmay,* 1930; *Monger,* 1966]. These NW vergent structures may provide the connection between the thrusts in the Northwest Cascades and the Coast Mountains of British Columbia. The bend in the thrust system may reflect the presence of the rigid mass of Wrangellia and the pre-mid-Cretaceous plutons of the southwestern Coast Belt in British Columbia [*Crickmay,* 1930; *Monger and Journeay,* 1994].

A markedly contrasting model is that the system is a broad, northwest striking dextral transpressive zone in which thrusts formed in contractional step over zones. The evidence for this interpretation is largely the regional development of northwest trending lineations [*Brown,* 1987; *Maekawa and Brown,* 1991; *Haugerud et al.,* 1994], although the kinematics are commonly inconclusive. We are impressed by the continuity of the Northwest Cascades system with structures elsewhere in the Coast Belt and thus favor the model that, overall, thrusting was directed to the SW.

The magnitude of thrusting is uncertain but must be large. Several tens of kilometers are required by the structural overlap, regardless of the transport direction [*Haugerud et al.,* 1994]. *McGroder* [1991] states that structural overlap requires a minimum of 47 km and 25 km on two thrusts of the belt. The presence of a large number of exotic slices in the thrust system [e.g., *Brandon et al.,* 1988] also implies large displacement.

## Regional Synthesis

**Reconstruction A.** Reconstruction A results in six coherent lithotectonic belts with distinct thrust fault zones forming most of their boundaries (numbered on Plate 2 and Figure 2). The coherence of the belts and similarity of large faults bounding the belts across reconstruction A (Plate 2) are what gives us confidence that it is viable. Many of these contacts are also terrane boundaries, which the mid-Cretaceous thrusting and strike-slip deformation have largely obscured. We feel that if a coherent reconstruction of the thrust belt can be obtained (Plate 2), this will greatly aid the analysis of these terrane boundaries.

On the northeast, belt 1 is the Methow terrane and the overlying Methow basin. To the southwest, belt 2 consists of Cadwallader terrane and overlying Tyaughton basin in the north and Bridge River terrane, its metamorphic equivalent (Napeequa unit of Cascades core), and the probable metamorphosed Cadwallader terrane (Cascade River unit of Cascades core) in the south. The two eastern belts are not separated by major thrusts, but by the younger dextral, strike-slip Yalakom, Fraser, and Hozameen-North Creek-Foggy Dew faults. In fact, the presence of identical rocks and thrusts in the northern part of the two belts is the primary evidence for the 115 km of dextral offset on the Yalakom fault [*Riddell et al.,* 1993]. *Garver* [1989, 1992] has demonstrated based on detailed provenance and stratigraphic evidence that the mid-Cretaceous sedimentary rocks of the Methow and Cadwallader belts were coniguous at that time. Both belts have early southwest vergent thrusts that formed from ~100 to 90 Ma. Northeast vergent thrusts cut these structures and were active from ~95/90 to 85 Ma. *McGroder* [1989] suggested that in belt 1, both groups of faults were active simultaneously and formed a tectonic wedge (B-B' in Figure 4) and northeast vergent faults outlasted the southwest vergent ones. Seismic reflection data further suggest tectonic wedging [*Varsek et al.,* 1993]. In belt 2, at present exposure levels the northeast vergent thrusts consistently cut the southwest vergent thrusts. Belt 2 contains the belt of Eocene deformation correlated across the Fraser - Straight Creek fault [*Coleman and Parrish,* 1991].

Belt 3 is the pelitic Chism - Settler - Chiwaukum Schists (Plate 2). The Cayoosh Assemblage of the Bridge River terrane [*Mahoney and Journeay,* 1993] may also be part of the pelitic schist belt [*Monger and Journeay,* 1994]. These pelitic schists have been correlated by previous workers based on similarities in lithology, geochemistry, and metamorphic histories [e.g., *Misch,* 1977; *Monger*

1986; *Evans and Berti,* 1986]. The Settler Schist possibly correlates to the Darrington - Shuksan units of the NW Cascades based on similar protolith composition, distinctive fabric in each unit, and the same structural position in the thrust stack [*Monger,* 1991]. This interpretation significantly enlarges the pelitic schist belt (Plate 2). Other workers, however, argue strongly against this correlation because of differences in Rb-Sr data and details of lithology between the two units [*Duggan and Brown,* 1994; *Haugerud et al.,* 1994].

Belt 4 is lithologically distinct from belts 2 and 3 and includes the Stikine terrane of the eastern Waddington area and generally similar rocks near Pemberton. Details of the stratigraphy of the two areas differ, but they both contain similar Triassic arc rocks and lack Jurassic sedimentary strata [*Riddell,* 1991; *Rusmore and Woodsworth,* 1991b], in contrast to the type Cadwallader terrane, which has a nearly complete Jurassic sedimentary section.

Belt 2 is juxtaposed against belts 3 and 4 across the (from NW to SE) eastern Waddington thrust belt, Bralorne - Kwoiek thrust belt, and White River shear zone. This boundary was probably a prethrust system (pre-100 Ma) terrane boundary as it separates very distinct rock units; alternatively, it may be a mid-Cretaceous terrane boundary [cf. *Tabor et al.,* 1987; *Umhoefer et al.,* 1994]. The eastern Waddington thrust belt is NE vergent [*Rusmore and Woodsworth,* 1994], was active from at or before 87 Ma to about 80 Ma, and shares much in common with the Castle Pass thrust belt in belt 2. The Bralorne - Kwoiek thrust belt and White River shear zones are continuous in the reconstruction and are similar in many respects. Both zones are NE dipping and place Bridge River terrane rocks over pelitic schists of belt 3. Timing on the White River shear zone is not well constrained, but latest movement is bracketed between 91 and 80 Ma (see above). The Bralorne - Kwoiek thrust belt was active from about 100 to 86 Ma, so the available age data permit the interpretation that the two thrust zones were active simultaneously. The belt 2-4 and belt 3-4 boundaries display relatively small, local slices of rocks correlated to the Bridge River terrane. These occur near the central Coast Belt detachment (CCBd) (Plate 2) of *Journeay and Friedman* [1993], a large out-of-sequence reverse fault. These relations suggest that the Bridge River terrane may underlie structurally parts of belts 2 and 3 (Figure 4b).

Belt 5, in the southwest, is separated from belt 3 by the central Coast Belt detachment of *Journeay and Friedman* [1993] and either its hypothetical extension near the Mt. Stuart batholith or the Windy Pass thrust fault, which places the ophiolitic Ingalls Complex over the Chiwaukum Schist [*Miller,* 1985]. The central Coast Belt detachment and Rock Lake shear zone within belt 3 near the Mt. Stuart batholith are northeast dipping thrust zones across which are abrupt pressure gradients with higher-pressure rocks on the northeast. The Windy Pass thrust, however, is mostly south dipping and may be a major back thrust. This structural boundary separates very distinct rock units, and it probably is a terrane suture zone. Belt 5 includes oceanic units that may correlate to the Bridge River terrane to the east [*Brown,* 1987].

Belt 6 is the Harrison Lake and Wrangellia terranes, which by middle Jurassic time probably were the same entity [*Monger and Journeay,* 1994; *Mahoney,* 1994]. Belts 3/4 (in the north) and belt 5 (in the south) are thrust over belt 6 along the (from north to south) central Coast Belt detachment, the Church Mountain thrust fault, and the frontal Haro thrust fault of the San Juan thrust belt, which may have been a linked set of faults during mid-Cretaceous thrusting [*Crickmay,* 1930; *Misch,* 1966], and mark terrane boundaries.

The position of magmatic belts also supports reconstruction A. The synthrusting (~100 - 80 Ma) magmatic belt is found in all reconstructed belts but belt 5 and is thus not an adequate test of the validity of the reconstruction. The postthrust system, ~80 - 60 Ma, magmatic belt, however, does have an impressive alignment in reconstruction A. Virtually all 80 - 60 Ma plutons lie in a narrow belt within reconstructed belts 2 and 4. In additon, many of these plutons are spatially and temporally associated with the early stage of dextral, strike-slip faulting on the Castle Pass, Downton Creek, and Ross Lake faults.

**Reconstruction B.** The differences between the two reconstructions are along the Fraser and Straight Creek faults, mainly in the southern half of the region. Reconstruction B does not align lithotectonic and structural belts as successfully as reconstruction A (compare Plate 2 and Figure 2), but it does satisfy some potential problems with A in the south. The Bridge River terrane rocks and metamorphic rocks in the Cascades core that have been correlated to them are not aligned in reconstruction B (Figure 2). Likewise, the Chism and Settler schists do not align with the similar Chiwaukum Schist in B. The Chiwaukum Schist is juxtaposed against blueschist and greenschist facies meta-basalts of the Shuksan Suite in B (Figure 2). Two interpretations may obviate these objections. First, there is some lithologic similarity between the Settler Schist and Bridge River rocks, although the Settler to Chiwaukum and Bridge River to Napeequa correlations seem much better by lithology [*Misch,* 1977; *Monger,* 1986; *Tabor et al.,* 1989; *Miller et al.,* 1993c]. Second, *McGroder* [1991] has advanced an argument that the Chiwaukum and Settler may be on opposite sides of a regional anticlinorium and therefore a specific spatial juxtapositon after restoration of the Straight Creek fault is not necessary.

The latter interpretations are weaker when the major structures in reconstruction B are also considered. The belt of steep thrusts near the Mt. Stuart batholith and the accompanying pressure gradient do not match the gently inclined faults in the Northwest Cascades thrust system to which it is juxtaposed (Figure 2). Similarily, the major Bralorne - Kwoiek thrust belt has no apparent match to the SE in reconstruction B. The White River shear zone, however, does approximately line up with the central Coast Belt detachment, and these structures may be similar in size and style, although the White River shear zone does appear to have been active later.

The weaknesses of reconstruction A relative to B relate primarily to restorations across the Straight Creek fault in the southern part of the region. The most problematic relationship is the match in reconstruction A between serpentinite melange of Manastash Ridge on the east side of the Straight Creek fault (MR on Plates 1 and 2) and the Helena-Haystack melange on the west side, both of which contain similar distinctive block types. [*Miller and Vance*, 1981; *Miller et al.*, 1993b; *Tabor et al.*, 1994]. Reconstruction A also does not account as well for possible westward continuations of the ophiolitic Ingalls Complex in the Northwest Cascades. In reconstruction A, the Ingalls Complex is on strike with the very different southwestern Coast Belt of British Columbia, whereas in B the ophiolite is nearly on strike with the Twin Sisters dunite, which is probably the root of a dismembered ophiolite of the Northwest Cascades [*Vance et al.*, 1980].

**Along-strike variations in the southern Coast Belt.** In our favored reconstruction A (Plate 2), the southern Coast Belt thrust system is 250 km wide in the south and ~200 km wide farther north after thrusting (Plate 2). It would be 300 km wide in the south if we extrapolated the Methow basin area along strike to the southeast. The wider system in the south is because of the great flap of low-angle thrusts of belt 5, which appear to have moved farther southwest over the Wrangellia - Harrison Lake footwall than the areas to the north (Figure 4). The style of thrusting is generally similar in both the southeast and northeast. Thrusting is spatially associated with mid-Cretaceous magmatism that was active during some part of the thrusting in all areas except the belt 5. This aspect of belt 5 may indicate that a major transfer zone is required along its northern margin.

The thrust system has deeper crustal levels exposed in the south and shallower levels in the north, but this may be partly an artifact of the areas that have been studied. High-grade rocks are exposed east of Harrison Lake [*Brown and Burmester*, 1991; *Journeay and Friedman*, 1993] and along the western edge of the eastern Waddington thrust belt in the north [*Rusmore and Woodsworth*, 1994]. The lack of study northwest of Harrison Lake makes it possible that high-grade rocks exist along the central part of the whole southern Coast Belt.

The areas of mixed northeast and southwest dipping thrust faults are primarily in the northeast, near the Tyaughton - Methow basin of belt 1 in our reconstruction (Plate 2), whereas the central and southern areas of the southern Coast Belt are dominated by northeast dipping thrusts. Analysis of seismic reflection profiles also shows mixed dips of faulting mainly in the southeastern Coast Belt [*Varsek et al.*, 1993]. However, the wholly southwest dipping eastern Waddington thrust belt in the northern end of our study area is in the southeastern Coast Belt; thus there may be a change to the north to dominantly southwest dipping thrusts. This interpretation is currently difficult to judge because of the lack of research southwest of the eastern Waddington thrust belt. Because most of the southwest dipping thrusts are spatially associated with the Tyaughton - Methow basin, perhaps the contrast between the relatively weak clastic section in the basin and the region to the west of voluminous plutons promoted thrusting toward and within the basin.

**Implications of reconstructions for *McGroder's* [1991] structural analysis.** The most comprehensive kinematic analysis of mid-Cretaceous contraction in the southern Coast Belt is that of *McGroder* [1991], who estimated a minimum of 400 km of E-W shortening across the North Cascades from the Northwest Cascades system to the eastern Cascades fold belt. Although acknowledging the problems presented by orogen-parallel strike-slip faults, *McGroder* [1991, p. 202] ignored them (except for vertical displacement) arguing that they did not prevent a "conceptually meaningful geometric construction."

Our preferred strike-slip reconstruction indicates significant specific problems with *McGroder's* [1991] model, although it provides general support for large shortening and the style of faulting he portrayed. The major problem with the McGroder model is that thrusts in the eastern Cascades foldbelt are far removed from the inferred correlative structures in the Cascades core and Northwest Cascades system. For example, the Chuwanten thrust appears to die out ~ 100 km NW of its presumed correlative, the Jack Mountain thrust (Plate 2), and thus it is unlikely that these thrusts are correlative. Rather, the Chuwanten probably cuts down beneath the Castle Pass thrust system in the Bridge River - Bralorne area, and the projection of the Jack Mountain thrust is probably buried beneath the Columbia Plateau. Our reconstruction causes less severe problems for *McGroder's* [1991] continuation of structures between the Cascades core and the Northwest Cascades system, although thrusts in this system are ~ 75 km south of their position in McGroder's cross section. We also note that his correlation of the Skagit Gneiss of the northeast Cascades core with the southwestern Coast Belt and the interpretation that this terrane underlies the Cascades core are contrary to our and others assignment of these rocks to the high-grade Bridge River and Cadwallader terranes of belt two [*Tabor et al.*, 1989; *Miller et al.*, 1993c, 1994; *Haugerud et al.*, 1994].

Despite these criticisms, the great width (up to 300 km) of the thrust system from the Northwest Cascades system to the projection of the eastern Cascades fold belt supports *McGroder's* [1991] interpretation of very large shortening. Thus his general conclusions are probably correct, although many of the specific correlations are not valid.

**Shortening across region.** Total shortening across the southern Coast Belt due to mid-Cretaceous thrust faulting is difficult to determine. One attempt to balance a cross section across the belt suggests 400 - 500 km of shortening [*McGroder*, 1991], but as discussed above, McGroder's model did not account for much of the strike-slip faulting, especially within the southeastern belt. Despite this problem, much of McGroder's analysis remains valid, the ≥50 km of shortening within the Methow basin and the ≥75 km shortening in the NW Cascades. This total of ≥125 km does not account for any shortening in reconstructed belts 2 and 3 of our model (Plate 2), where mainly metamorphic rocks make estimates of shortening difficult. We conclude that much more than 125 km of shortening took place across the southern Coast Belt during the mid-Cretaceous thrust faulting. We note that the two areas where shortening estimates are calculated constitute only ~50% of the width of the belt and therefore we might infer that ≥250 km of shortening across the belt is a reasonable minimum estimate if shortening was fairly evenly distributed and that the 400 - 500 km shortening estimated by *McGroder* [1991] is possible.

## Discussion

### Why Rotation in the Reconstructions?

The Coast Belt is divided across a line from 49°N on the west to 50° 30' N on the east; north of that line the belt trends about due northwest, and south of that line it trends more northerly or north-northwest (Plate 1). Because of this change in strike, restoring blocks along dextral, strike-slip faults creates large gaps, which we minimized by letting the blocks rotate as we reconstruct them. But what is the geologic explanation for this change in orientation of the southern Coast Belt?

We propose that two tectonic mechanisms at different times in the Cenozoic can explain the relative rotation and argue that because of this rotation the belt was not bent during mid-Cretaceous thrusting (Plate 2).

1. The most compelling answer may be that the large bend occurred during regional Eocene extension in the southeastern Coast Belt and the southern Intermontane and Omineca Belts to the east. In the Eocene, ~100 km of WNW-ESE extension occurred in the southern Omineca Belt [*Tempelman-Kluit and Parkinson,* 1986; *Parrish et al.,* 1988] directly east of the Methow basin. At the same time in the Eocene, the southwestern Coast Belt was experiencing northward translation along dextral, strike-slip faults and local extension. The net effect of these two regional strain patterns may have been to rotate the southern and eastern parts of reconstruction A clockwise relative to the northern part, because the northern and western areas were moving northwest along dextral-slip faults while the southern and eastern areas were within the zone of major WNW-ESE extension.

2. The bend is close to alignment with the bend in the present outer margin of the Pacific Northwest at the Olympic Mountains. *Brandon and Calderwood* [1990] suggested that crustal structural patterns in the Olympic Mountains and the bend in the margin may best be explained by clockwise rotation of the Pacific Northwest south of the Olympics due to Miocene to Recent Basin-and-Range extension that is present east of the Oregon coast and dies out to the north. This mechanism is the same as what we envision for the Eocene, but in a more southern position.

### Relationships Between Plutonism and Thrusting in the Southern Coast Belt

It has been increasingly recognized that plutons in the roots of some arcs were emplaced during regional contraction [e.g., *Tobisch et al.,* 1995; *Hutton,* 1992]. The Coast Belt represents perhaps the largest such recognized arc, as mid-Cretaceous plutonism and thrusting occurred for a distance of over 1200 km along strike. Most studies of this arc have focused on tectonostratigraphic relationships, but several relatively recent papers have documented the interaction between plutonism and contraction [e.g., *Hollister and Crawford,* 1986; *Miller and Paterson,* 1992; *Rusmore and Woodsworth,* 1994; *Ingram and Hutton,* 1994; *Paterson et al.,* 1994].

A striking feature of the southern Coast Belt is that mid-Cretaceous thrusts in the flanks of the belt, such as the Northwest Cascades - San Juan Islands system, are relatively gently dipping but steepen significantly within the zone of abundant plutons (Figure 4). This does not represent a simple foreland-hinterland transition, as most contractional faults dip steeply NE in the foreland to the Harrison Lake thrust belt, which is composed largely of plutons. In addition to their steepness, some of the major structures in the southeastern Coast Belt domain are late-stage, out-of-sequence thrusts that carry synthrusting plutons in their hanging wall [*Journeay and Freidman,* 1993]. This suggests that the steepness of the thrusts may be related to the intrusion process or to the presence of these relatively rigid bodies.

The effect of magmatism on the mechanics and location of thrusts in the Coast Belt is still poorly understood. *Hollister and Crawford* [1986] emphasized that melt generation resulted in major tectonic surges in the northern Coast Belt and that magmatism led to thermal weakening of the belt. We have also noted above that the sparse, high-angle thrusts active after 90 Ma were localized along pluton margins. Many synthrusting plutons, however, apparently experienced only minor subsolidus deformation [e.g., *Miller and Paterson,* 1994; *Paterson et al.,* 1994]. On a larger scale, thin-skinned faulting ended in the southwestern domain during widespread magmatism but continued in the pluton-poor southeastern domain.

An ongoing controversy is the relationship of pluton emplacement and major crustal loading within the Cascades core. Several workers have documented nearly isothermal pressure increases of 2 to 6 kbar during Cretaceous metamorphism [*Evans and Berti,* 1986; *Brown and Burmester,* 1991; *Brown and Walker,* 1993; *Miller et al.,* 1993a; *Sawyko,* 1994] and attributed them to either loading by thrusts of the Northwest Cascades system [e.g., *McGroder,* 1991] or to loading by now eroded plutons [*Brown and Walker,* 1993]. The considerable width (> 250 km) of the mid-Cretaceous thrust system, as indicated by our reconstructions, supports the interpretation that thrust loading was the more important mechanism. Crustal thickening by thrusting occurred in areas with no or few Cretaceous plutons, such as in the Northwest Cascades system, where structural burial is manifested by low-temperature/high-pressure metamorphism that accompanied thrusting or was slightly postdated thrusting [*Brandon et al.,* 1988]. Nevertheless, the relatively circular isobaric surfaces constructed by *Brown and Walker* [1993] for parts of the Cascades core are difficult to explain by thrust loading and more work is needed to evaluate the magma loading hypothesis.

### Southern Coast Belt Thrust System and Plate Tectonics

Our study and a review of the southern Coast Belt geology strongly reinforces previous interpretations [e.g., *Engebretson et al.,* 1985; *Umhoefer,* 1987] that a major change in tectonic style at ~85-80 Ma was caused by a change from the Farallon to Kula plate along the southern Coast Belt or a major change within the Kula plate [*Engebretson et al.*, 1995]. Widespread ~110-80 Ma magmatism and thrust faulting was followed from 80 to ~60 Ma by a narrow zone of magmatism and dextral-slip+thrust faulting on the east side of the southern Coast Belt. In all areas of the southern Coast Belt, there is a similarity in the timing of the cessation of major, widespread thrusting at 90 to 80 Ma. Coeval (110 - 80 Ma) arc magmatism is widespread and voluminous in the region, and sedimentary basins lay on the northeast side of the belt. From 80 to ~60 Ma, there are no basinal rocks preserved in the southern Coast Belt and magmatism is found only in a narrow belt in the southeastern Coast Belt.

The profound change in the southern Coast Belt at 85-80 Ma was from contractional deformation oriented normal to the orogen (WSW-ENE) to dextral-transpressional deformation with dominantly NW to north striking faults. This is exactly what is expected if the Farallon plate subducted normal to the southern Coast Belt (North America) during the ~110 to 85 Ma interval and the Kula plate subducted obliquely northward after ~80 Ma as predicted in plate motion models [*Engebretson et al.*, 1985; *Engebretson, et al.*, 1995]. The continuity of the Coast Belt from Washington to SE Alaska [*Rubin et al.*, 1990] suggests that the entire Coast Belt lay along the Kula plate after 80 Ma and the Kula-Farallon-North America triple junction lay at the southern end of the Coast Belt. The location along western North America of the major plate boundary change at ~80 Ma summarized here from evidence in the southern Coast Belt is dependent on resolution of the Baja British Columbia controversy [e.g., *Cowan*, 1994].

## Conclusions

1. The southern Coast Belt thrust system consists primarily of northeast dipping thrust faults with southwest vergence. Nearly all faults of the southeastern and southwestern domains and early stage faults of the southeastern domain are SW vergent.

2. An important belt of southwest dipping thrust faults with northeast vergence is in the northeast adjacent to, and within, the Tyaughton - Methow basin. Where both northeast and southwest dipping faults are documented, the northeast dipping faults are older.

3. Much of the thrust system has thin-skinned faulting and folding, especially at the eastern and southwestern margins. However, thick-skinned, moderate to high-angle thrust faults are common, particularly as late-stage, out-of-sequence faults in the central part of the belt. These differences are probably related to synthrusting magmatism in the interior of the belt and not in the margins.

4. Tectonic wedging at the tens of kilometer to kilometer scale is strongly suggested in seismic reflection sections [*Varsek et al.*, 1993] and from local geometric relations in the Methow basin [*McGroder*, 1989]. Tectonic wedging is difficult to prove in most places because the northeast vergent thrusts cut the southwest vergent thrusts.

5. The suggestion for the earliest thrusting in mid-Albian time (~105-100 Ma) is from stratigraphic observations of local unconformities and locally sourced conglomerate clasts in the Tyaughton - Methow basin [*Garver*, 1989; *McGroder*, 1989], but elsewhere the initiation of thrusting is uncertain. Structures in synkinematic plutons indicate that thrusting was widespread by 96 Ma. Major southwest vergent faulting ceased at 92-91 Ma in many areas; relations interpreted on seismic reflection lines suggest that northeast vergent faulting accompanied this and formed large-scale tectonic wedges.

6. After ~90 Ma, the former areas of southwest vergent faulting had either a few major, high-angle, out-of-sequence thrusts that were still southwest vergent or had a dominance of northeast vergent thrusts that cut the older faults. This second stage lasted until 85 - 80 Ma.

7. Magmatism was widespread in the southwestern Coast Belt from ~96 to ~80 Ma, or throughout most of the time of thrusting. Magmatism in the southeastern belt was sporadic and scattered before 90 Ma, and then from 90 to 80 Ma a major volcanic sequence was erupted over much of the southeastern domain (Plate 1). This magmatic pattern and the timing of thrusting suggest that low-angle, thin-skinned faulting died in the southwestern and western part of the southeastern belts at ~90 Ma because of the large volume of magma that intruded the middle and upper crust. Note that the few major, high-angle thrusts that became active after 90 Ma are located along the margins of large plutons, which truncate earlier structures. The post-90 Ma northeast vergent thrusting was accompanied by eruption of thick andesites in the Tyaughton - Methow basin.

8. Estimates of shortening are ≥125 km from two segments in the southwestern and northeastern parts of the belt, while estimates of shortening for the central part of the belt are not yet possible. These local estimates suggest that approximately ≥250 km of shortening occurred across the entire southern Coast Belt and that the 400 - 500 km suggested by *McGroder* [1991] is possible.

9. We infer from a comparison to plate motion studies [e.g., *Engebretson*, et al., 1995] that the Farallon plate was being subducted under the southern Coast Belt during mid-Cretaceous thrusting and magmatism. At ~85-80 Ma, the Kula plate started to converge with very oblique, northward motion along the southern Coast Belt as indicated by the dramatic decrease of magmatism and switch to more localized dextral+thrust faulting.

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